Fermi National Accelerator Laboratory

FN-469

A Phase Space Tomography (PST) Monitor for Adjusting Bunch Rotation During Coalescing

G. Jackson
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 26, 1987

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

A PHASE SPACE TOMOGRAPHY (PST) MONITOR
FOR ADJUSTING BUNCH ROTATION DURING COALESCING

G. Jackson

November 26, 1987

Table of Contents

Introduction and Motivation

While discussing general beam diagnostics problems with Jim Crisp, the problem of ascertaining the structure of longitudinal phase space repeatedly arose. Thinking about a bunch in phase space rotating at the synchrotron frequency, and about the information one gains from present beam detectors, the association between this problem and that of doctors doing a CAT scan of a patient became apparent.

When a doctor needs to know the position of a tumor in a patient, a now common procedure is to put the person in a special X-ray machine. Instead of exposing a piece of photographic film to a single burst of radiation through the body, an array of matched X-ray tubes and electronic detectors are rotated around the patient, measuring the attenuation of each X-ray beam as a function of angle. This attenuation data is digitized and sent off to a computer.

In 1917, the Austrian mathematician J. Radon published a paper proving that any two-dimensional object can be reconstructed from the infinite set of its projections. Given a sufficient number of projections, and using some ingenious mathematical algorithms, it is possible to reconstruct the structure of an object with a finite set of projections.

Applying these algorithms to the X-ray attenuation data from the patient, the computer generates a two-dimensional density profile of the person. It is typical to describe densities by employing a false color scale, hence generating some of the fascinating pictures of human brain and heart cross sections commonly found in glossy journalism.

What does this all have to do with coalescing in the Main Ring? Imagine replacing the X-ray intensity detectors with a resistive wall current detector, and the patient by a proton beam. Now, instead of the patient remaining motionless, the beam rotates in phase space while the wall current monitor always measures the time domain projections of its density profile. Digitizing voltage as a function of time for each turn over a quarter of a synchrotron period, sufficient information is gathered to use the above algorithms to reconstruct the longitudinal phase space density distribution of the beam.

This document is a proposal for construction of a first generation model of such a monitor, used to study Main Ring coalescing during the bunch rotation phase of that operation. It will be shown that a monitor of this kind is ideal for understanding bunch dynamics during rotation, such as recapture timing and the different rotation rates for each bunch due to mistuning of the 5 MHz linearization RF system. Toward the end, a number of next generation schemes are proposed for future consideration.

Coalescing and Bunch Rotation

The high energy physics detectors scattered around the Tevatron expect periodic collisions of single proton bunches against single antiproton bunches. In order to attain useful luminosities, the design intensity for each of these bunches is $6x10^{10}$ particles. The problem is that this number far exceeds the intensity per bunch which can be produced by either the Booster or Accumulator rings. Coalescing is the process by which the charge from a number bunches is stacked into a single Main Ring RF bucket.

In detail, the coalescing scheme envisages up to eleven bunches rotated in longitudinal phase space by a lower frequency 2.5 MHz RF bucket, into a single 53 MHz bucket. Before rotation commences, the primary 53 MHz RF voltage is reduced such that the bunch lengths are as long as possible. At this point the bunch rms approaches 3 ns. The rotation RF voltage is then turned on.

Since the RF voltage is sinusoidal, and 11 bunches occupy half of the 2.5 MHz period, not all bunches would rotate in phase space at the same rate. To rectify this, a lower voltage 5.0 MHz is also turned on to linearize the RF waveform in the region occupied by the bunches. Figure 1 shows the result of a least square calculation of the optimum 5.0 MHz voltage as a fraction of the 2.5 MHs voltage. Note in the lower frame of figure 1 that the test particles sown in the top frame have rotated fairly uniformly. At the standard coalescing momentum of 150 GeV/c in the Main Ring, with the presently available 2.5 MHz and 5.0 MHz voltages, the rotation process requires thousands of turns. Figure 2 is a phase space representation of 3 stages of an idealised rotation manipulation. In the top frame the 11 bunches have the same energy, each occupying their individual 53 MHz RF buckets. The center frame shows the bunches half way through their rotation into the single bunch shown in the bottom frame.

Once the bunches have been rotated in phase space such that they fit within the period of a 53 MHz wave, the primary 53 MHz RF voltage is snapped back on, capturing the new, single bunch.

Electronics

The resolution with which the structure of a human heart can be reconstructed depends on the spacing of the collimated X-ray beams through the patient. Similarly, the resolution with which the PST monitor can reconstruct phase space depends on the sampling rate of the wall current detector output voltage. Given the present state of ADC and memory technology, a modest and cheap bunch dynamics monitor, with a resolution of approximately 2 nsec, is easily constructed from components already in use in present Tevatron superdamper electronics.

The SONY corporation manufactures an 8-bit, 100 MHz flash ADC (CX20116/CXA1066K) which, with the help of a transistor charge pump on its input, has a 200 MHz input bandwidth. Since the goal of this monitor is to identify the centroid of bunches, this bandwidth is sufficient. Because the ADC can only do one sample every 10 nsec, a number of ADCs are required to digitize an entire RF bucket. Figure 3 is a proposed schematic of one channel of such a ADC array. Once per 53 MHz clock cycle a convert trigger is sent to the channel. The result of each conversion is placed in memory. A SONY digital delay line FIFO chip (CXK1202S) is well suited for this application. By alternating between two chips, each of which is 8-bit with an access time of 25 nsec and maximum memory length of 1144 words, and reading them out to the control system as 16 bit words, an efficient and convenient readout system can be readily synthesized with existing control system CAMAC cards. Because each ADC would convert for each of the 11 bunches, a maximum of 200 turns can be stored.

Figure 4 is a rougher schematic of the controller card which would need to be built. First, note the architecture of the proposed 9 channel PST monitor. By introducing a 2.09 nsec delay between the convert pulse and beam signal down the chain of channels, one convert pulse per RF bucket will cause the bunch to be digitised into 9 evenly spaced portions. The convert trigger pulses must occur in bursts of 11 per turn, once every Nth turn. These pulse trains should start occurring when the 2.5 MHz RF system is turned on, and turned off when the 53 MHz RF system is snapped back on. Counting the number of turns per conversion is necessary for both the reconstruction process and for some higher level diagnositics which can be done later at a control system console.

The ADCs can be acquired for around $100 a piece, and are probably the dominant hardware cost of the project. Assuming another thousand or so dollars for miscellaneous hardware and construction, a safe estimate for the cost of such a monitor is well under $3000. Figure 5 is a simulated mountain range of projections which such a monitor would produce.

Reconstruction Algorithms

There exist two simple algorithms for reconstructing an image from a set of its projections. The figures of merit for comparing these two methods of calculation are speed and reproduction quality. Both have been coded into a VAX program. The following figures are outputs of this program, which has been given simulated projection data. The bunch rotation model, which assigns rotation rates and bunch pair intensities, is located in the box on the top right hand side of each figure.

Summation Method

The summation method is the simplest algorithm to envisage. Assume the object to be reconstructed lies on a matrix with the same pixel dimensions as the voltage conversion separation. Each voltage conversion each turn represents a unique line through this matrix. Calculating the trajectory of each line and adding the value of the projection to each matrix pixel it traverses, a reconstructed image of the original object is produced.

Assume that there is only one bunch at the center of rotation, and that it does not change bunch length during the rotation manipulation. In such a circumstance, every projection would be identical. The center frame of figure 6 shows the result of the summation method when only six projections are taken over 180° of phase space rotation. The pixel at the center of the picture has a value six times higher than any other pixel.

When 400 projections are taken of the same 180° rotation, the coherence effect at the center of the picture in the bottom frame of figure 6 makes the reconstructed center bunch much more clear. 180° worth of data is not necessary for this algorithm, it just makes the reconstructed image more symmetrical.

The same principle holds for a generalized phase space picture. The center frame of figure 7 shows the 180° reconstruction of 11 bunches rotated in an ideal fashion. Note the lack of grey scale resolution. If one biases the grey scale phase space density calculation by setting pixels below a certain threshold to zero, the bottom frame is produced.

Though the summation method is the most direct algorithm for reconstructing an object from its projections, there is a more precise method. Similar to the summation algorithm, it utilizes a recursive approximation approach to image synthesis.

ART Method

Let us assume that the matrix contains some approximation to the original phase space density distribution. Projections can be taken of this approximation and compared to the original projections. By taking the difference between the new and old projection values, and subtracting the difference from all the pixels through which the projection traverses, the reconstructed image is forced to agree on a ray by ray basis with the original. By iterating this calculation, a progressively better image emerges. In addition, by adding constraints such a forcing a minimum pixel value of zero, the convergence of this method can be dramatically improved.

Figure 8 is a comparison between an original simulated phase space rotation scenario and its 90° reconstructions by 1, 2, and 5 ART iterations. The initial state of the matrix was all zeroes. First, note that even the first iteration has much better contrast than that produced by the summation method. Second, note that the difference between the first and second iterations indicates a very fast convergence rate. As confirmation, the fifth iteration is better, but not all that much better than the second.

It turns out that the superiority of the ART generated reconstructions over those created by the summation method is increased when bunch rotation is mistuned, and all bunches have not all rotated by 90°. Since a single ART algorithm is roughly the same speed as the summation method (about 20 sec on ADCALC for 200 turns), it seems reasonable to concentrate on using the ART method. There are some tricks available which can probably speed up the computer code by a factor of two or so.

Bunch Rotation Examples

There are two classes of rotation problems which should make this monitor extremely useful as a diagnostic. Once the 2.5 MHz and 5.0 MHz RF systems are turned on, the person tuning coalescing must know when to turn on the 53 MHz RF system. In other words, the operator must know when the bunches have rotated by exactly 90°. Tuning using the F0 frame grabber is possible, but the accuracy one can achieve is severely limited by noise and resolution.

Figure 9 shows the original and reconstructed final state of the bunches after a mistimed rotation manipulation. Though mistimed by a gross amount in this example, smaller rotation mistimings would be easily diagnosed by calculation of a least square fit of the bunch centroids to a line.

The second class of rotation problems is centered around the optimum setting for the 5.0 MHz RF voltage. Mistuning by small amounts can cause the bunches to rotate into an S shaped figure in phase space. Diagnosing and tuning this effect with the mountain range is extremely difficult.

Figure 10 again shows the original and reconstructed final state of the bunches after phase space rotation, where the outermost pair of the bunches has been instructed to rotate slower than the rest. Note the excellent imaging of this scenario, even though the fact that part of phase space is rotating at a rate different from the rest violates the assumptions inherent in this monitor. Again, using fitting algorithms on the pixel data, one could automatically calculate 5.0 MHz voltage corrections from the control system primary application controlling this monitor.

The time (horizontal) axis is the only dimension in which a measured scale can be applied. The energy (vertical) axis of figures 8 through 10 is not directly measured. On the other hand, since the synchrotron frequency is a measured quantity, one can produce a model dependent vertical axis which should be quite accurate. Assume that the 5.0 MHz RF voltage is tuned to roughly its optimum value. Then the scale ratio between the vertical and horizontal axis is Ω/η, where Ω is the angular synchrotron frequency and η is the momentum compaction. Since η is a well known quantity, an accurate vertical scale can be applied to the data. If one inputs the rotation and recapture RF voltages, buckets can be superimposed on the data. This information, along with information available from fits to the image data, should make such a monitor very useful for accelerator operations.

Future Designs

There are a number of accelerator questions which could be answered with a next generation model of the PST monitor, capable of digitising with a resolution on the order of 100 psec. The technology for such a monitor, namely the use of sampling diodes and holding capacitors, is potentially more expensive and complicated than the plan for the first generation monitor outlined in this paper. On the other hand, the application of such a monitor could help diagnose problems ranging from phase space dilution at injection to instabilities.

As an example, imagine such a monitor in the Tevatron during colliding beam stores. Dipole and higher order longitudinal bunch oscillation modes are known to exist in the colliding bunches. With more bunches and higher intensities, coupled bunch modes may start to manifest themselves. A high resolution PST monitor, capable of presenting either phase space or pure time domain information, may prove to be invaluable in diagnosing and correcting such problems.

Experience with the first generation monitor and modeling of potential problems, such as those discussed in the previous paragraph, should indicate if such a high resolution monitor is desirable. Therefore, such a PST monitor design should be left for future discussion.

Conclusion

A monitor capable of reconstructing the final state of bunch rotation in phase space during the coalescing process is possible. Such maladies as rotation mistiming and 5.0 MHZ RF voltage mistuning are easily diagnosed with such a PST monitor. Given the measured synchrotron frequency and the theoretical momentum compaction, energy information can be extracted from the data, making tuning of the rotation and recapture RF systems much more visual and direct.

Acknowledgement

The seed for this idea, and much of the initial direction of the subsequent research, was a direct effect of discussions with Jim Crisp. The history and algorithms of the tomography reconstruction process came from an October 1975 Scientific American article (233, No. 4, pg. 56) by R. Gordon, G. Herman, and S. Johnson. The design of the electronics came from discussions with Brian Fellenz and Don Martin. The questions regarding integrating such a monitor into the existing control system were answered by Mike Glass.

Fig. #1

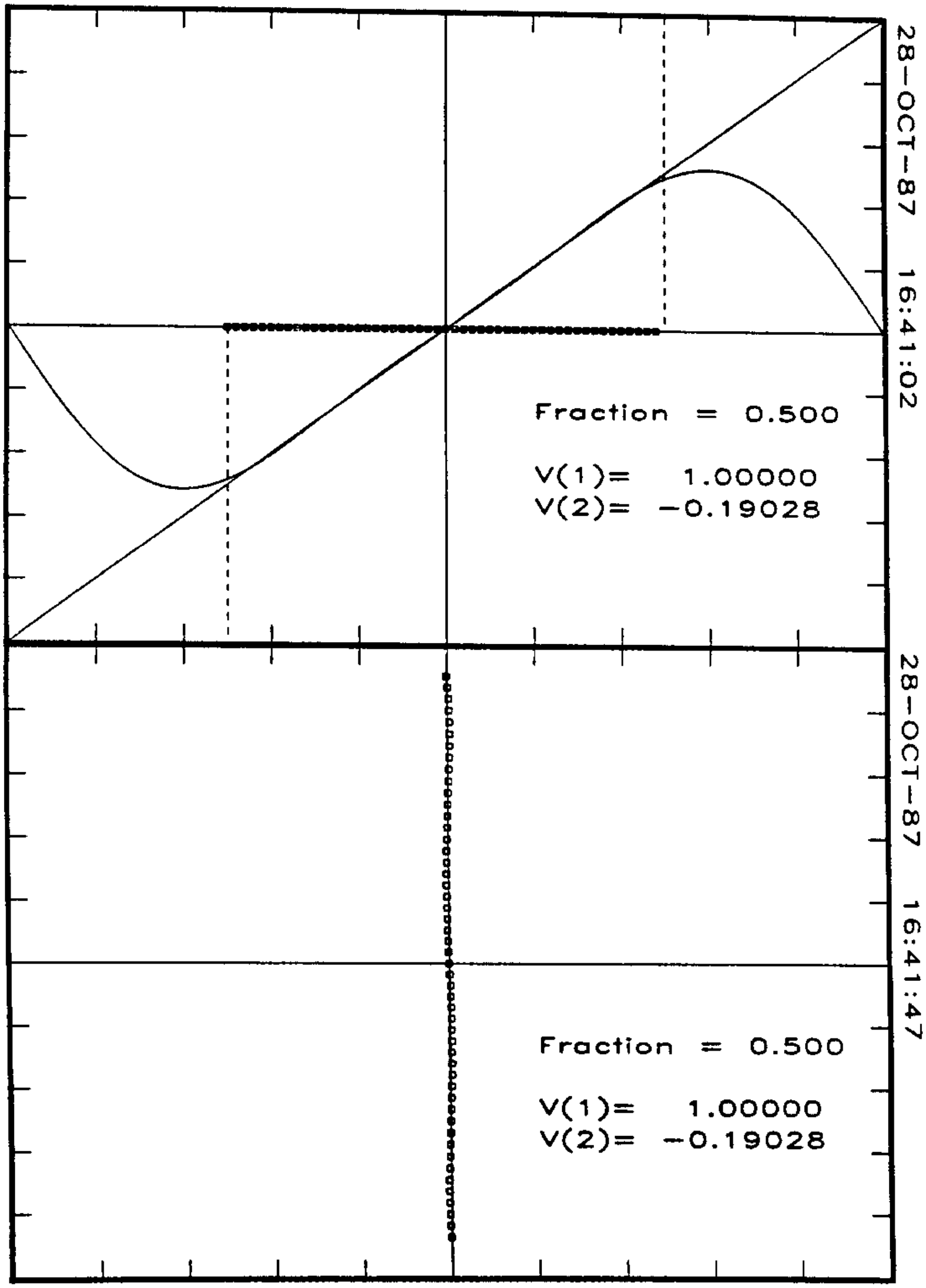
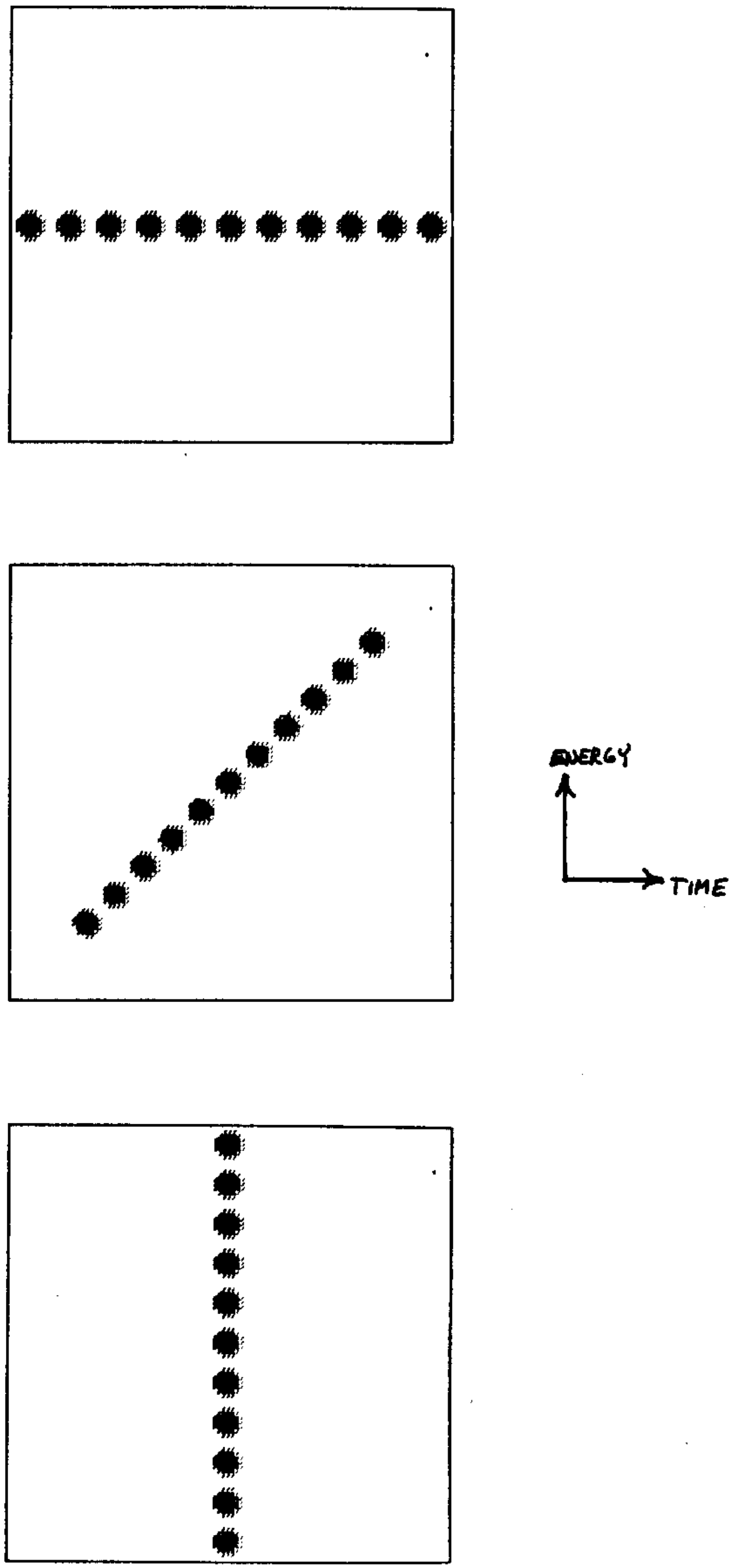
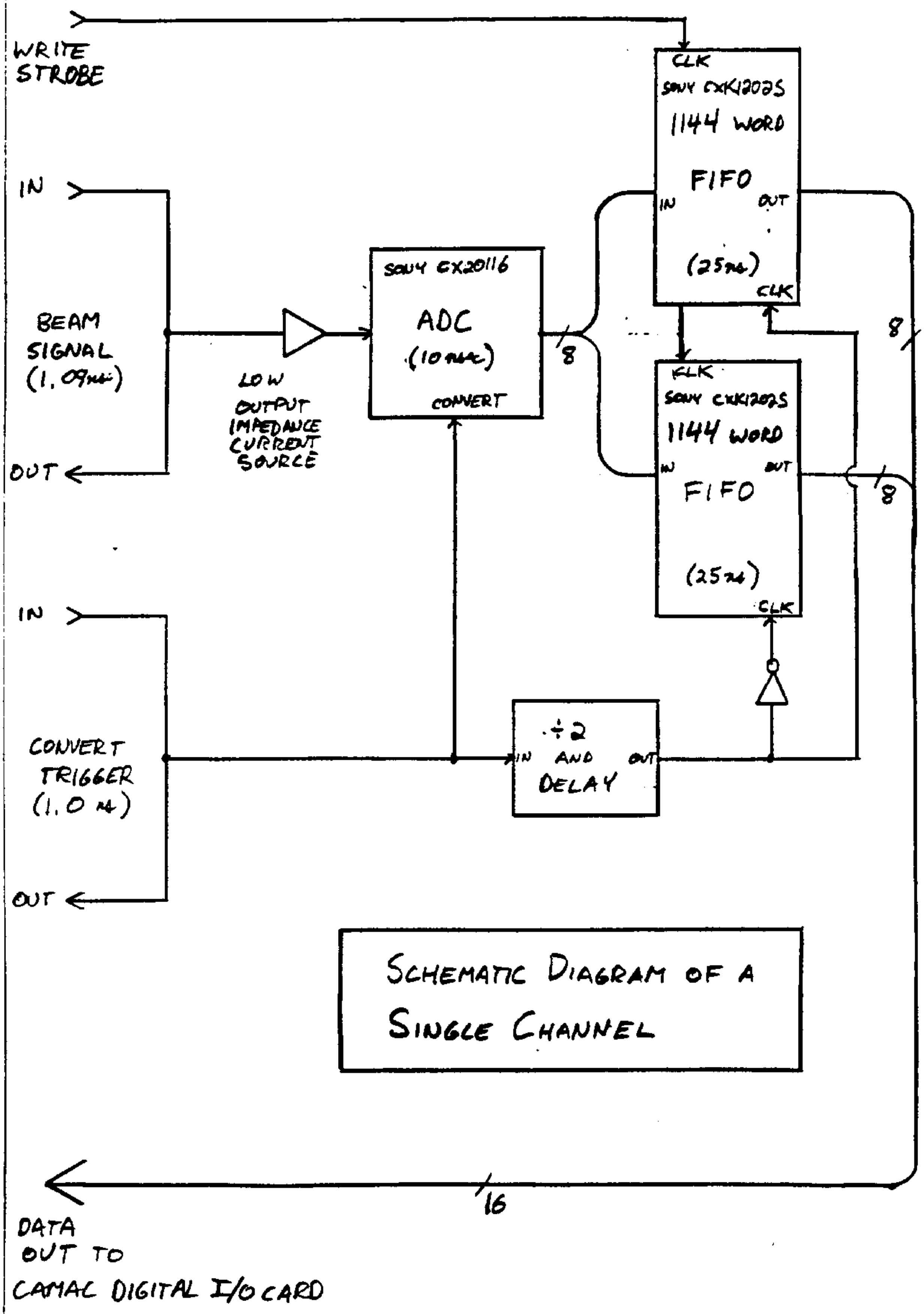

28-OCT-87 16:41:02
Fraction = 0.500
V(1)= 1.00000
V(2)= -0.19028
28-OCT-87 16:41:47
Fraction = 0.500
V(1)= 1.00000
V(2)= -0.19028

FIG. #2



11/11/87

Fig. #3



Schematic Diagram of a Single Channel

11/12/87

SCHEMATIC DIAGRAM OF CONTROLLER CARD

FIG. #4

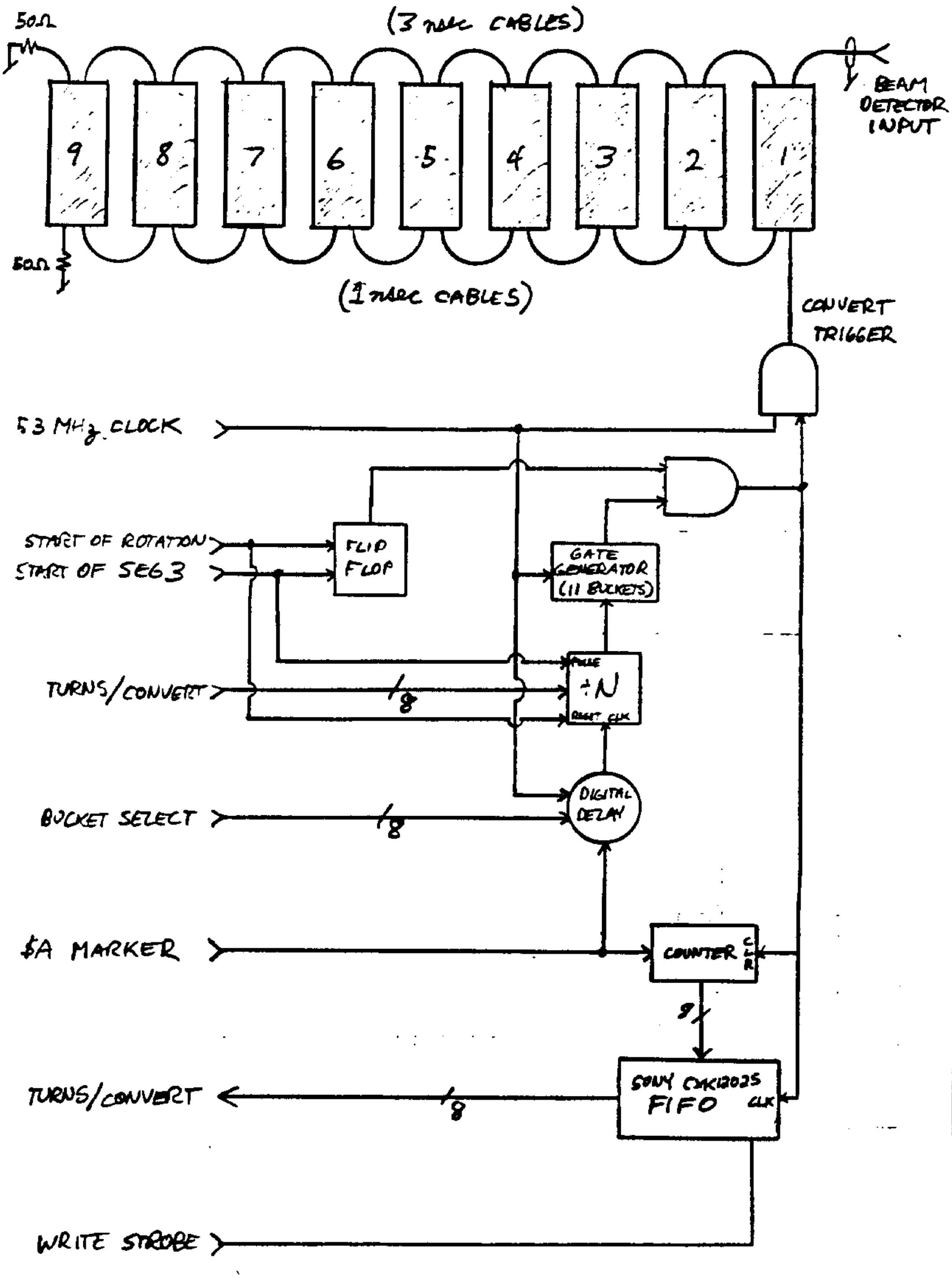
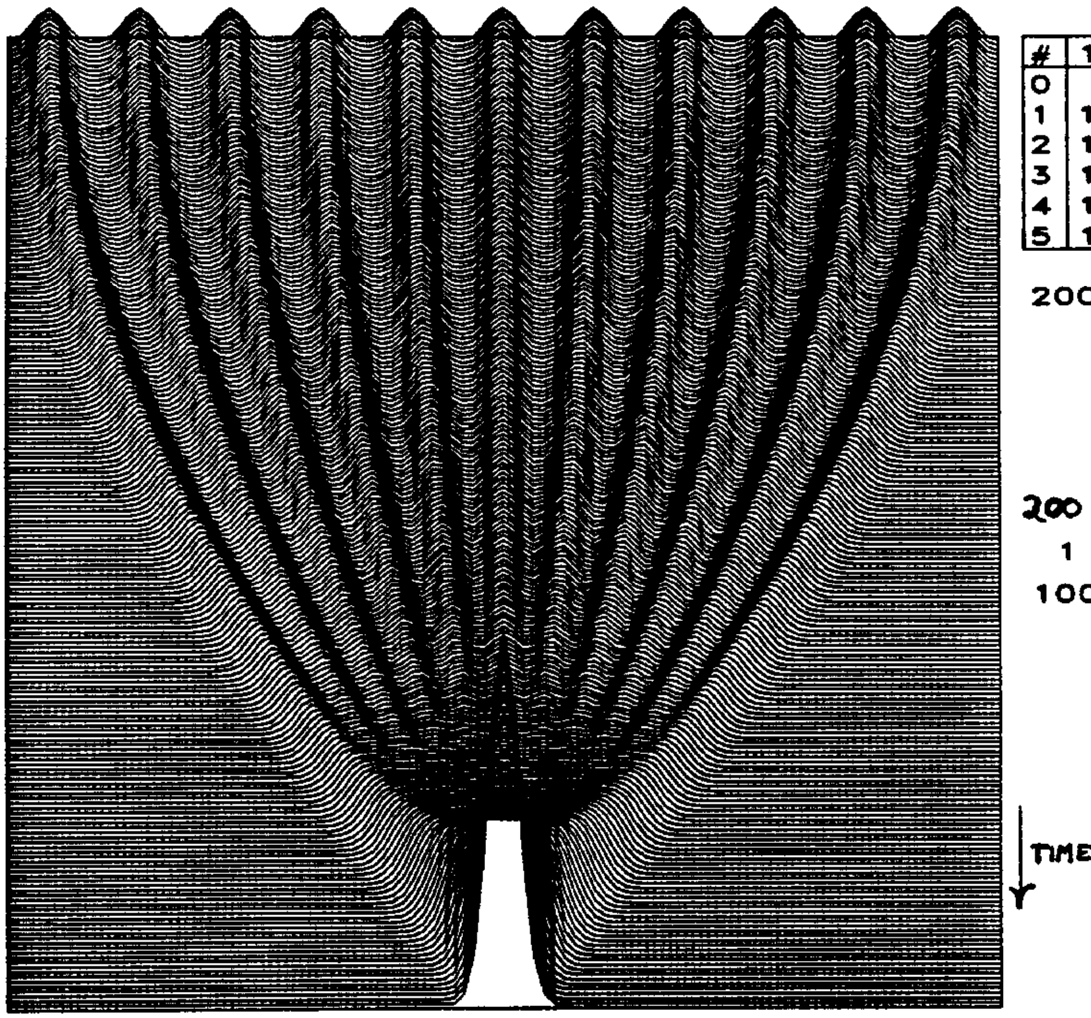


FIG. #5

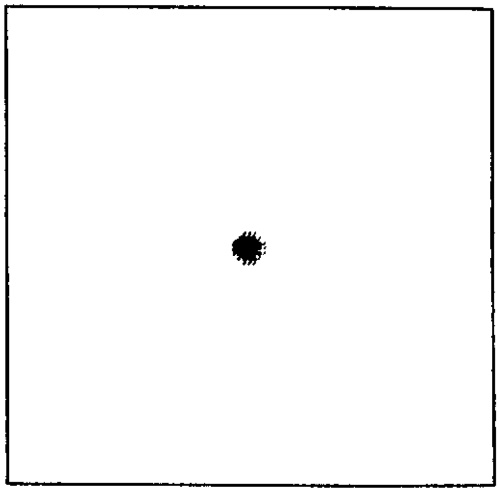


#	1E8	90d
0	55	200
1	110	200
2	110	200
3	110	200
4	110	200
5	110	200

200 #/90d

200 Sweeps
1 #/Sw
100 Gain

FIG. #6

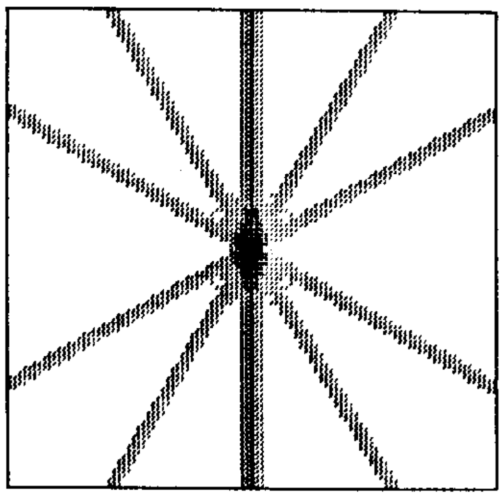


#	1E5	90d
0	55	200
1	0	200
2	0	200
3	0	200
4	0	200
5	0	200

200 #/90d

7 Colors
100 Gain
0 Off

Original

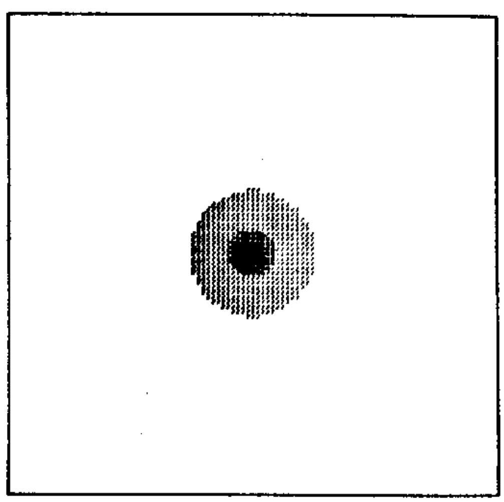


#	1E5	90d
0	55	200
1	0	200
2	0	200
3	0	200
4	0	200
5	0	200

3 #/90d

7 Colors
100 Gain
0 Off

Reconstructed



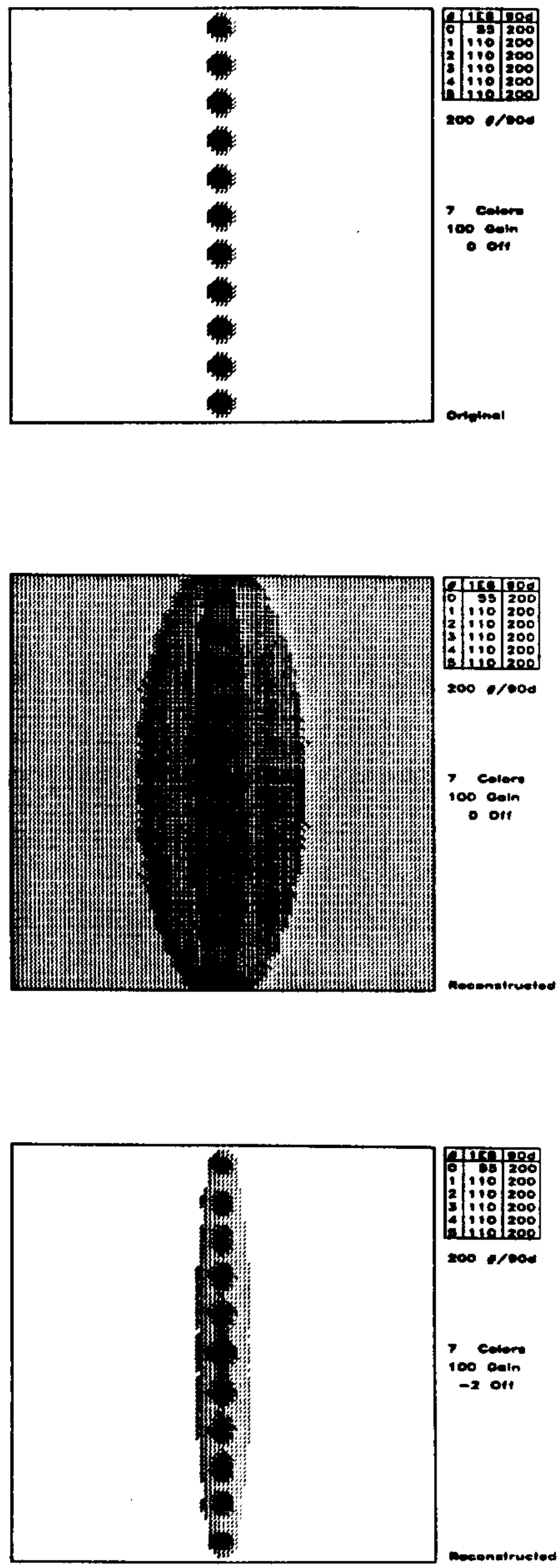
#	1E5	90d
0	55	200
1	0	200
2	0	200
3	0	200
4	0	200
5	0	200

200 #/90d

7 Colors
100 Gain
0 Off

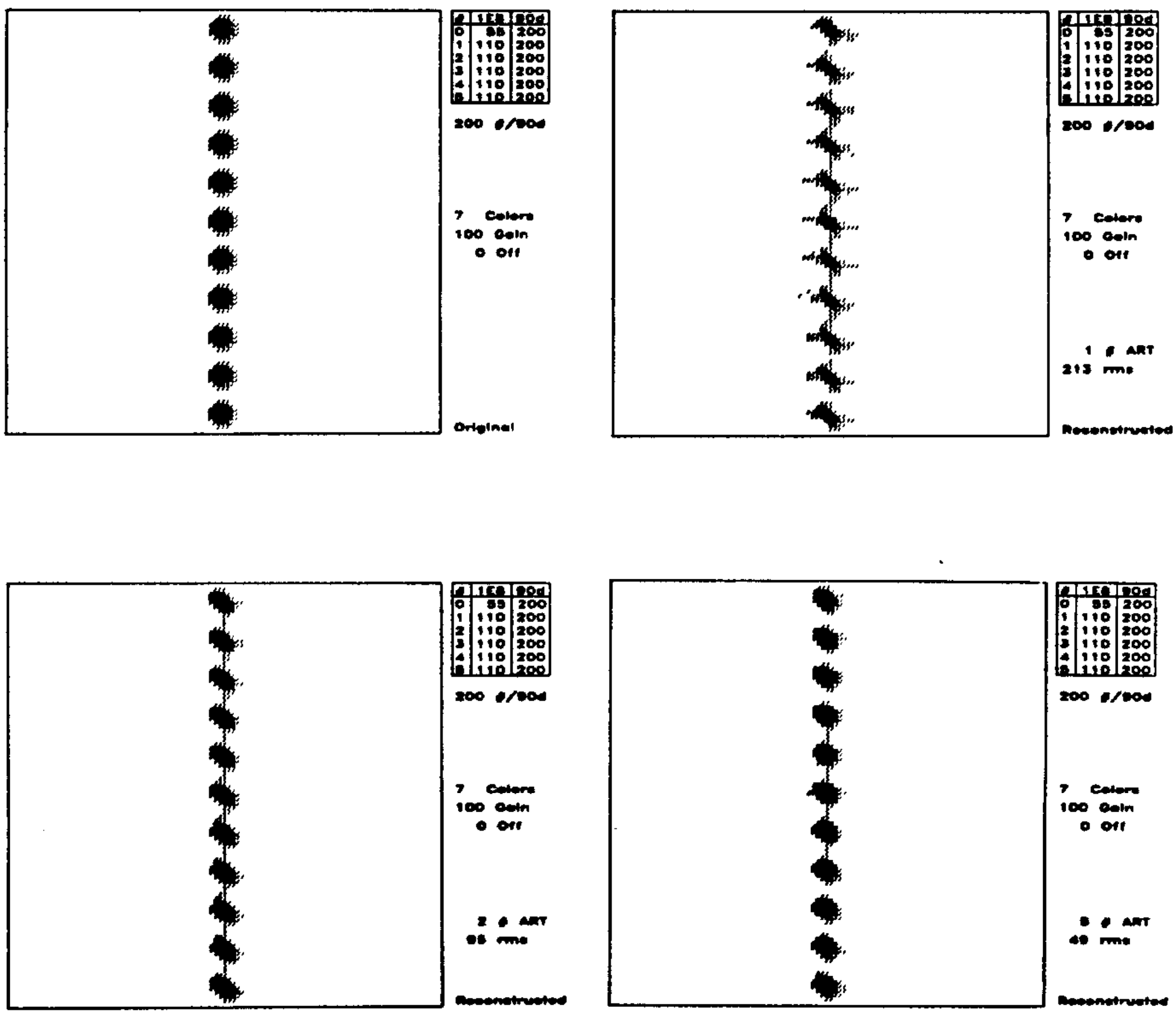
Reconstructed

FIG. #7



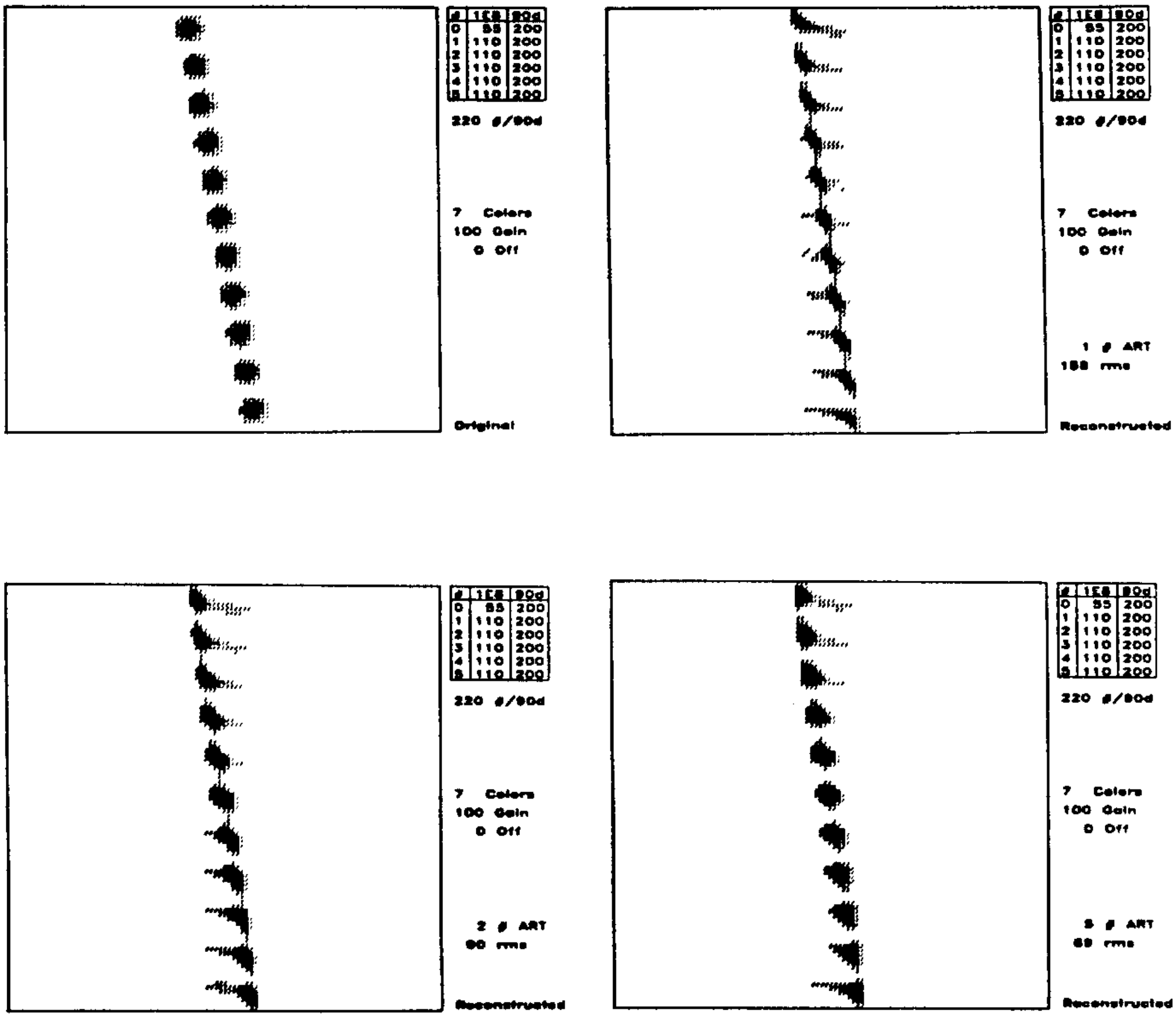
1E8 90d
0 95 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
Original
1E8 90d
0 95 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
Reconstructed
1E8 90d
0 95 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
-2 Off
Reconstructed

Fig. #8



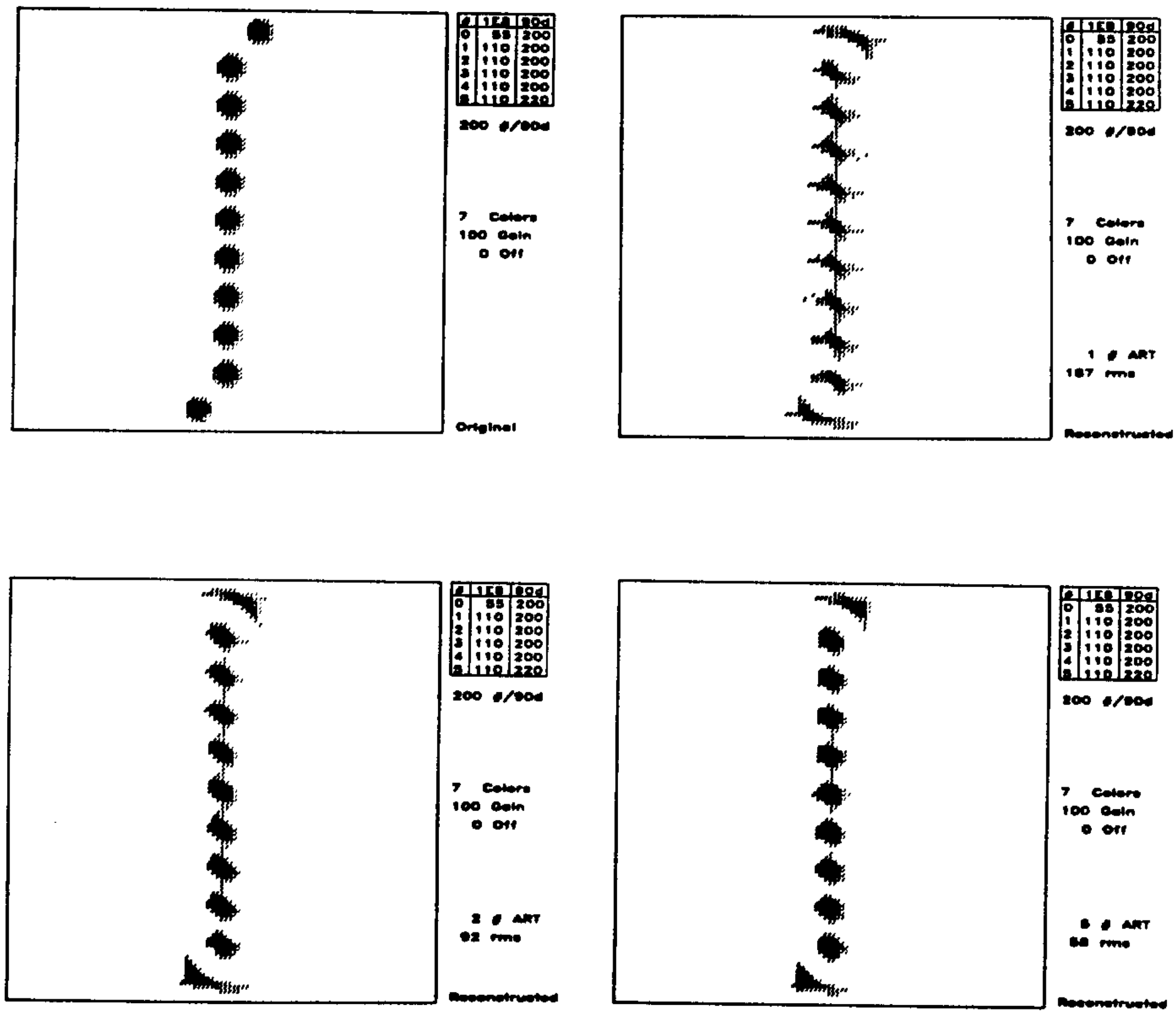
1E8 90d
0 55 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
Original
1E8 90d
0 55 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
1 # ART
213 rms
Reconstructed
1E8 90d
0 55 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
2 # ART
95 rms
Reconstructed
1E8 90d
0 55 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
200 #/90d
7 Colors
100 Gain
0 Off
5 # ART
49 rms
Reconstructed

Fig. #9



1E8 90d
0 85 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
220 #/90d
7 Colors
100 Gain
0 Off
Original
1E8 90d
0 85 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
220 #/90d
7 Colors
100 Gain
0 Off
1 # ART
158 rms
Reconstructed
1E8 90d
0 85 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
220 #/90d
7 Colors
100 Gain
0 Off
2 # ART
90 rms
Reconstructed
1E8 90d
0 85 200
1 110 200
2 110 200
3 110 200
4 110 200
5 110 200
220 #/90d
7 Colors
100 Gain
0 Off
3 # ART
69 rms
Reconstructed

Fig. #10



200 #/90d
7 Colors
100 Gain
0 Off
Original
1 # ART
187 rms
Reconstructed
2 # ART
92 rms
5 # ART
58 rms